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## 9th International Conference on Axiomatic Design – ICAD 2015

## Design of test parts to characterize micro additive manufacturing processes

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**Abstract**

The minimum feature size and obtainable tolerances of additive manufacturing processes are linked to the smallest volumetric elements (voxels) that can be created. This work presents the iterative design of a test part to investigate the resolution of AM processes with voxel sizes at the micro scale. Each design iteration reduces the test part size, increases the number of test features, improves functionality, and decreases coupling in the part. The final design is a set of three test parts that are easy to orient and measure, and that provide useful information about micro additive manufacturing processes.

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**1. Introduction**

The minimum feature size and obtainable tolerances of additive manufacturing (AM) processes are linked to the smallest volumetric elements (voxels) that can be created. Although theoretical minimum voxel sizes can be calculated for many AM processes, analytical models don't always account for the true complexities of a given process. In addition, the hardware and settings used in commercial systems are not always known; there are always variations in machine construction, material quality, digital workflow, and postprocessing procedures; and, all manufacturing systems are subject to external disturbances such as vibrations and fluctuations in temperature and humidity. Thus, the true precision and resolution of a given machine can't be determined without producing, measuring, and characterizing parts with features near the voxel limit of the system.

This work presents the iterative design of a test part to investigate the resolution and repeatability of AM processes with voxel sizes at the micro scale. Each iteration improves the design by identifying and removing coupling, uncovering new requirements, and introducing new design parameters. The result is a set of three test parts with good usability that provide clear information about the resolution of the 3D printer that produced them.

The paper begins with a review of existing additive manufacturing test parts, artifacts, and benchmarks. It introduces the design process for the test parts and the equipment and procedures used to produce and measure them. Each of the three design iterations is discussed in detail. Future work to correct known design flaws, (in)validate design assumptions, and increase the type and quality of results are discussed. The paper concludes with a discussion of the benefits of using Axiomatic Design Theory and TIRZ in the design and redesign of micro additive manufacturing test parts.

**2. Prior art**

The design, production, and measurement of standardized test parts (also referred to as test artifacts, benchmarks, or benchmark parts) is the most common way to evaluate the performance of additive manufacturing machines and processes [1]. A variety of AM test parts exist (e.g. [2-5]), however these usually focus on the macro scale behavior of additive manufacturing systems. For example, the smallest test features found in a recent review of the AM benchmark literature “were 0.25mm thin walls (for both polymer-based and metal-based AM processes), 0.2mm diameter holes and bosses in polymer-based AM processes, and 0.5mm diameter

holes and bosses in metal-based AM processes” [1]. In contrast, this work considers cubic and cuboid test features with critical dimensions ranging from 5µm to 100µm.

### 3. Methods

#### 3.1. Design process

Most design processes are orderly procedures where stakeholders are identified; stakeholder needs are collected and translated into various types of requirements; solutions to meet the requirements are proposed and evaluated; and the best solution is selected for prototyping, testing, and further development. In this work, the stakeholders were easy to identify (as the designers also served as the manufacturing and metrology engineers) but the full set of stakeholder needs, and therefore the functional requirements and constraints, could not be determined in advance. Even if these had been known, the interactions between the functional requirements, design parameters, and process variables would have been difficult to predict. Instead, design iteration, supported by prototypes and experiments, was used to simultaneously explore the problem and solution spaces until the designers “converge[d] on a matching problem-solution pair” [6]. Principles from Axiomatic Design Theory [7-8] and TRIZ [9] guided the evaluation and redesign processes by helping to identify and remove coupling and contradiction from each design iteration. However, no formal methods were used. No decompositions were performed and no design matrices were constructed during the project.

#### 3.2. Test part production

The designs presented in this work are generic and applicable to a wide range of additive manufacturing processes. However, they were developed for digital light processing (DLP) 3D printing. Sample test parts were produced using RCP30 on an EnvisionTEC Perfactory® Mini Multi Lens 3D Printer with standard settings and an 85mm lens.

#### 3.3. Measurement

The test part features were measured using an Alicona InfiniteFocus G4 microscope. The measurement characteristics of the Alicona depend on the objective used (table 1) [10].

Table 1. Measurement characteristics of the Alicona with various objectives.

	5x	10x	20x	50x
Field of View (x) (µm)	2858	1429	715	286
Field of View (y) (µm)	2175	1088	544	218
Finest Lateral Resolution (µm)	3.52	1.76	0.88	0.64
Finest Vertical Resolution (µm)	0.410	0.100	0.050	0.020

Smaller magnifications offer a larger field of view and therefore a larger measurement area, at the cost of measurement resolution and quality. The measurement area is rectangular and is defined by the field of view. For example, the measurement area with the 5x objective is 2.858x2.175mm. The measurement area with the 10x objective is 1.429x1.088mm.

Stitching multiple fields of view increases the measurement area at the cost of a small increase in measurement (stitching) error. The maximum area that can be stitched is limited by the data file size and the computer memory: as the file size increases, so does the probability that the computer will crash during measurement. The file size is determined by the number of measured data points and therefore is a function of the measurement footprint, the measurement height, and the vertical and lateral resolutions. From experience, we know that it is easy to perform 5x7 stitches using the 5x objective and its maximum vertical and lateral resolutions. A 9x12 stitch using the 10x objective and its maximum vertical and lateral resolutions is impractical.

After measurement, the Alicona (.AL3D) file was opened, the surface form was removed, and the data was postprocessed in SPIP™.

### 4. First design iteration

The first test part was developed as a general benchmark and included features with many shapes and sizes (figure 1). The base of the part was 20x20x2mm. The features raised the maximum height of the test part to 3mm.

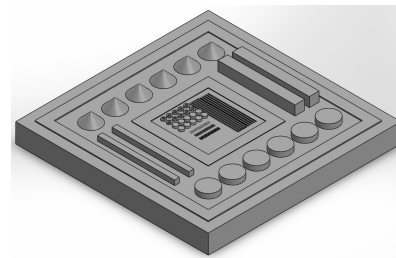


Fig. 1. Solid model of first test part (isometric view)

To support micro additive manufacturing research, the benchmark included 3 sets of 60 features (20 rows with 3 features per row) located in the center of the part (figure 2). The smallest features were intended to represent a single voxel on the EnvisionTEC. The EnvisionTEC has a minimum layer thickness of 15µm and a native pixel size of 16µm using the enhanced resolution module (ERM) and an 85mm lens [11]. Therefore, the first set of features were specified as 16x16x15µm in the solid model. The other features were supposed to be 2x2x2 voxels (modeled as 32x32x30µm) and 3x3x3 voxels (modeled as 48x48x45µm). The features had a spacing of 100µm (measured from the upper left corner of one voxel to the upper left corner of the next). Since this specification was based on the leading edge of each cuboid, the spacing decreased with each set of features. This resulted in effective spacings of 84µm, 68µm, and 52µm. Each set of features was separated by 300µm.

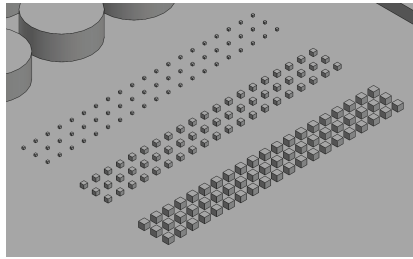


Fig. 2. Solid model of micro scale features on first test part (isometric view).

The measurement of the first test parts revealed two design flaws. First, the largest ( $3 \times 3 \times 3$ ) features were too close together. The resin used for printing (RCP30) has a high viscosity. Excess resin became trapped between the features during printing and was cured onto the part during postprocessing. As a result, these features were fully formed but physically coupled and therefore indistinguishable from each other (figure 3). This could be addressed (and the system uncoupled) by increasing the space between the features, by modifying the postprocessing procedure to remove excess material (to the extent possible), or by using a lower viscosity resin (thereby reducing experimental freedom). In this work, the first option was chosen and implemented in the second design iteration.

Second, the smallest features on the first test part did not print (figure 3). Therefore, the native voxel size could not be confirmed and the smallest printable feature size could not be determined.

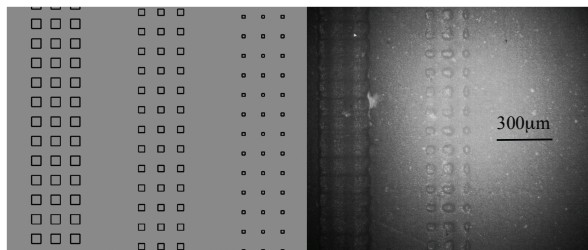


Fig. 3. First design iteration of test part: top view of solid model features (left) and corresponding image of 3D printed sample (right). Image taken with a standard Leica camera at 5x magnification.

## 5. Second design iteration

The second test part was designed specifically to characterize micro manufacturing processes. The base of the second test part was  $14 \times 14 \times 2$  mm with a  $0.5 \times 0.5$  mm raised border to protect the features during handling and storage. This resulted in a total part height of 2.5 mm (figure 4).

The second test part contained 12 sets of 25 cubes (figures 5 and 6). These were designed with dimensions from  $10 \times 10 \times 10 \mu\text{m}$  to  $65 \times 65 \times 65 \mu\text{m}$  with an increment of  $5 \mu\text{m}$  between sets. The cubes had a spacing of  $300 \mu\text{m}$  (measured from the center of one cube to the center of the next) for a minimum effective spacing of  $235 \mu\text{m}$  (approximately 4.5x more than in the first design). Each set of cubes had a spacing of 3 mm (measured from the center of the first cube in each set

to the center of the first cube in the next set). This resulted in an effective spacing 1.8 mm between sets (approximately 6x more than in the first design). The cube dimensions were chosen to provide more information about the true voxel size of the machine and the process being tested. The cube spacing was chosen to avoid physical coupling between features.

The measurement of test parts from second design iteration also revealed several design flaws. As with the first test part, many of the smallest features did not print. Only half of the features ( $40 \mu\text{m}^3$  and up) were consistently present. This was larger than the smallest features printed on the first test parts (nominally  $32 \times 32 \times 30 \mu\text{m}$ ) and far larger than the minimum voxel size reported by the manufacturer ( $16 \times 16 \times 15 \mu\text{m}$ ). Therefore, the second iteration also failed to identify the minimum voxel size on the EnvisionTEC.

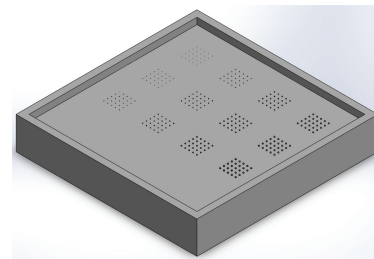


Fig. 4. Solid model of second test part (isometric view)

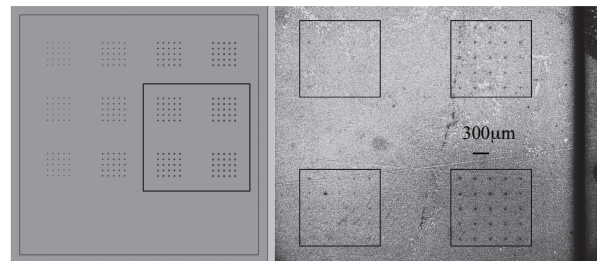


Fig. 5. Second design iteration of test part: full solid model (left) and close up image of four sets of 25 features from 3D printed sample (right). Image taken with a standard Leica camera at 1.6x magnification.

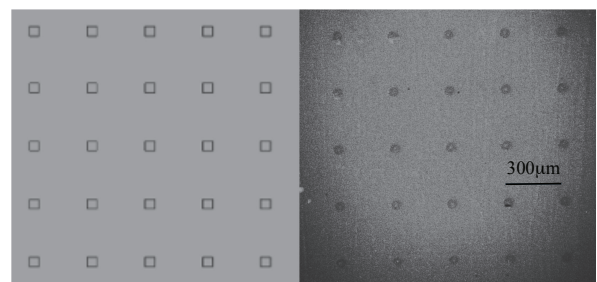


Fig. 6. Group of 25 features ( $65 \mu\text{m}$  cubes) from second design iteration: solid model (left) and image 3D printed features (right). Image taken with a standard Leica camera at 5x magnification.

Next, it was difficult to differentiate small printed features from surface damage and debris. For example,  $35 \mu\text{m}^3$  features may or may not have been present. The best way to



distinguish small printed features from unwanted debris was by location. (Something that looks like a printed feature in a location that is supposed to have a printed feature probably is a printed feature. Since debris is randomly distributed and features are regularly spaced, the quality of this assumption improves with the number of suspected features present.) Unfortunately, the part was not designed to facilitate the identification of features by location. The part was too large to stitch the full feature set on the Alicona and the smaller features sets were too far from the larger ones for a partial stitch to help. Therefore, it was impossible to identify features after measurement. The spacing between sets of features was also too large to hunt for features manually.

Finally, the only information available about the correct orientation of the test parts came from the micro scale features. These could not be seen and therefore the parts could not be oriented without the help of a microscope.

## 6. Third design iteration

The third iteration included a number of changes to address the problems with the first two designs. First, the footprint of the test parts was decreased to facilitate stitching while the height was increased to make the parts easier to handle. Each new test part was a 10x10x5mm block with a 0.5x0.75mm raised border (figure 7). In addition to being taller, the new border design included two 1.0x0.25x0.5mm channels in the top left and bottom right corners to indicate the x and y axes of the part. The channels are visible to the naked eye and can be used to orient the part before imaging.

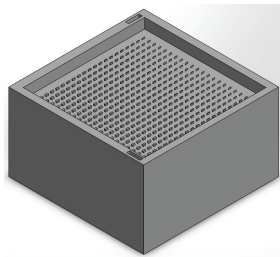


Fig. 7. Isotropic view of solid model for third design iteration of the test part (variation in x).

Features on the new parts were organized in 20 rows with 20 features per row. Rows and columns were placed 400 $\mu$ m apart (measured from the leading edge of one feature to the leading edge of the next) for a minimum effective spacing of 200 $\mu$ m. The spacing between features was large enough to prevent the viscosity related problems observed in the first test parts and small enough to easily find and view features with the Alicona at high magnification. Because the footprint of the full 20x20 feature set (8x8mm) was small enough to be imaged using a 5x objective with a 5x7 stitch, features could also be identified during data postprocessing. For example, figure 8 shows a horizontal cross section through a test part in an area where features are absent. Only surface roughness and surface form can be observed. Figure 9 shows a horizontal cross section through a nearby set of features with similar surface roughness and form. Note that all 20 features are

present. Figure 10 shows a vertical cross section through 20 sets of features on a different test part. Note that the smallest of the 20 features seems to be missing.

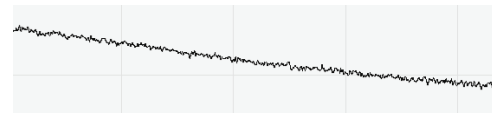


Fig. 8. 8mm long horizontal cross section through a test part in a region with no features. Slope represents real surface form, not measurement error.

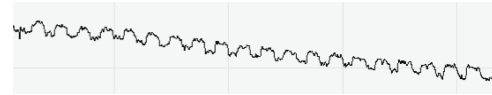


Fig. 9. 8mm long horizontal cross section through one row of z test features with design dimensions of 200x200x10 $\mu$ m. Actual voxel height ~15 $\mu$ m. Slope represents real surface form, not measurement error.

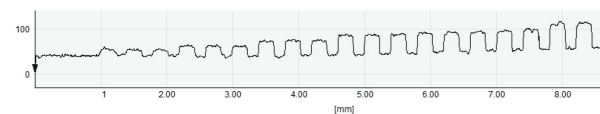


Fig. 10. Vertical cross section through one column of z test features with dimensions of 200x200xZ $\mu$ m.

Each feature in the third design iteration had one dimension that was ‘small’ and variable and two dimensions that were fixed and ‘large’. This was done to eliminate coupling between the dimensions and ensure that only one variable was tested at a given time. It also helped to ensure that all printed features could be found.

Finally, each test sample contained features with variations in only one dimension (x, y, or z). Thus, three test samples were needed for a complete set. The x sample features were Xx200x100 $\mu$ m where X varied from 5 to 100 $\mu$ m in increments of 5 $\mu$ m. The y sample features were 200xYx100 $\mu$ m where Y varied from 5 to 100 $\mu$ m in increments of 5 $\mu$ m. The z sample features were 200x200xZ $\mu$ m where Z varied from 5 to 68 $\mu$ m in increments of 1 $\mu$ m or 5 $\mu$ m (figure 11).

The third design iteration was far more successful than its predecessors. The test parts were easy to orient and measure and the test features were easy to locate. The test parts from this design have also provided usable data sets and interesting insights into the DLP 3D printing process. For example, the x and y samples showed that the EnvisionTEC will attempt to print features with a specified length or width of 10 $\mu$ m. (The actual printed dimensions vary.) The z samples confirmed that the EnvisionTEC rounds vertical dimensions up or down to the nearest print layer thickness [12]. They also showed that the true layer thickness of the printer is slightly less than 15 $\mu$ m and that the top faces of the features become “gradually smaller and more rectangular as the height increases” [12].

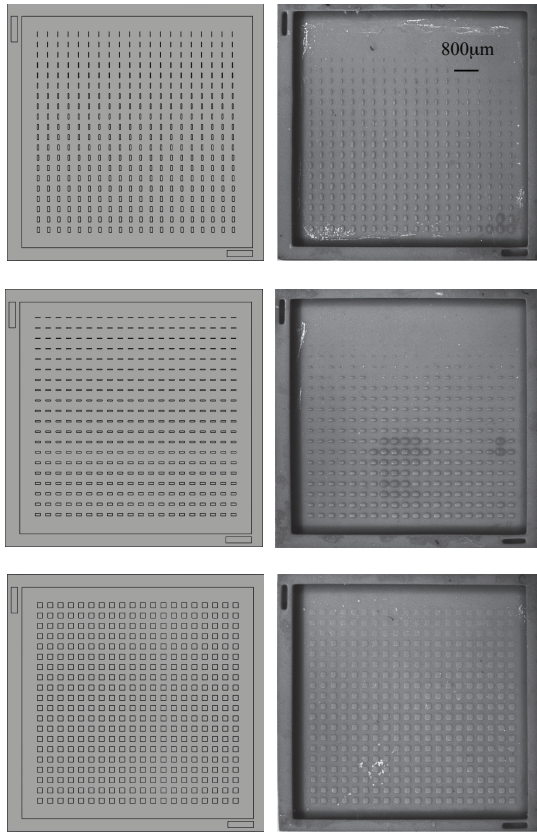


Fig. 11. Third design iteration of test part with variation in x (top), y (middle), and z (bottom): full solid model (left) and image of 3D printed sample (right). Image taken with a standard Leica camera at 1x magnification.

## 7. Evolution of the test part

A summary of the key design parameters for the three design iterations is given in table 2. During its evolution, the footprint of the test part steadily decreased, while the total number of test features per part, the number of test feature sets per part, and the spacing between test features increased. Each design iteration introduced new test part features and functionality. Finally, each design iteration decreased the coupling in the part. For example, the second design iteration removed the coupling between adjacent features due to the viscosity of the photopolymer resin, while the third design iteration removed the coupling of the voxel dimensions by increasing the number of design parameters per voxel and the number of test parts per experiment from one to three.

## 8. Future work

Although the third design iteration was the first to produce usable results, it is far from the last version expected in the series. Future design iterations will correct newly discovered design flaws, test and (in)validate design assumptions, and increase the type and quality of information that can be collected from the test features.

Table 2. Comparison of key design parameters for the three design iterations

	Design 1	Design 2	Design 3
Base Footprint (mm)	20x20	14x14	10x10
Base Height (mm)	2	2	5
Test parts per set	1	1	3
Feature shape	Cuboid	Cubic	Rectangular block
Sets of features per part	3	12	20
Features per set	60	25	20
Corner-to-corner spacing between features (µm)	100	300	400
Spacing between sets (µm)	300	1800	400
Total data set footprint (mm)	1.2x2	10.2x7.2	8x8

### 8.1. Correcting known design flaws

The samples from the third iteration were designed to be imaged with the 5x objective on the Alicona. However, the 5x objective on the Alicona (finest lateral resolution: 3.52µm) can provide only 2 or 3 data points for a 10µm feature. For reliable measurements of features with dimensions of 10µm or less, the 10x objective (finest lateral resolution: 1.76µm) or the 20x objective (finest lateral resolution: 0.88µm) must be used. Stitching the full 8x8mm data set using the 10x objective requires a 9x12 stitch. As noted above, this cannot be done reliably. Therefore, the footprint of future test feature sets should be reduced. This can be accomplished by reducing the number of features per part (e.g. 10x10 or 15x15 sets of features) and/or by reducing the spacing between features.

One way to compensate for the reduced number of features per test would be to increase the number of test parts per data set. For example, four test parts each with a 10x10 feature set could replace one test part with a 20x20 feature set. This would provide more information about the repeatability of the process and the variance between parts but less information about the repeatability and variance within each part.

### 8.2. Testing and removing assumptions

The third design iteration assumes that the voxels are cuboids. The features in figures 3 and 6 indicate that this may not be true. The third design iteration also assumes that the voxels are produced in a Cartesian coordinate system that is aligned with the design and printing coordinate systems. Thus, long thin features were only printed at 0 and 90 degrees. However, the true minimum could exist at some other angle. Finally, all of the test parts assumed that there is no spatial variation in voxel production. These assumptions have not been tested and therefore may not be true. It is expected that the test feature design will evolve as explicit and implicit assumptions are identified and either validated or invalidated.

### 8.3. Improving the type and quality of results

The first and second design iterations had test features with coupled dimensions while the third iteration was uncoupled and investigated one dimension at a time. Taken as a group, these three experiments indicate that there is interaction between the three dimensions and that this interaction increases the minimum printable feature size. However, none of the first three designs can be used to quantify this interaction. It is expected that the design of the test parts and test features will evolve to provide more and better information about the behavior of 3D printers at the micro scale and to better enable statistical analysis of the phenomena as the phenomena themselves are better understood.

## 9. Discussion

Although AD and TRIZ offer many tools and techniques for the designer, the most powerful aspects of these theories are also the simplest. Axiomatic Design Theory and TRIZ urge the designer to identify and remove sources of coupling in their designs. This eliminates the presence of or the potential for technical and physical contradictions. The reduction or removal of coupling improves performance, reduces complexity, and improves the designer's ability to predict, optimize, and control system performance. Therefore the identification and removal of coupling is an important step in the design process.

In this work, knowledge of AD and TRIZ allowed the designers to quickly recognize and remove coupling and contradiction in the design. The emergent nature of the requirements for micro additive manufacturing experiments made and will continue to make this design process iterative. However, the use of AD allowed and will continue to allow new problems to be identified and corrected in a single iteration. This will minimize the total number of iterations, improving the overall efficiency of the design process, and will reduce the time and cost of the associated experimentation.

## 10. Conclusions

This work presented the evolution of a test part designed to characterize the resolution of 3D printing processes at the micro scale. Each iteration reduced the test part size, increased the number of test part features, improved functionality, and decreased coupling in the design. The result

is a set of three test parts that are easy to orient and measure, and that provide useful information about the processes and equipment used to produce them.

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